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THESIS

A RELIABILITY STUDY OF RFID TECHNOLOGY IN A FADING CHANNEL

by

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June 2007

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RFID systems are an important component in the effort to increase the efficiencies of the logistics supply chain for the U.S. Department of Defense. While the U.S. DoD has mandated the use of RFID tags for its suppliers, the technology has not always kept up with the performance expectations.

This study explores new modulation and coding techniques to possibly be used in the improvement of the read reliability of RFID systems. Bit and tag error probabilities are computed for various OOK and M-CSK modulation schemes in a varying Nakagami-m fading channel, and the best performing schemes are identified for future employment.

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A RELIABILITY STUDY OF RFID TECHNOLOGY IN A FADING CHANNEL

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ABSTRACT

RFID systems are an important component in the effort to increase the efficiencies of the logistics supply chain for the U.S. Department of Defense. While the U.S. DoD has mandated the use of RFID tags for its suppliers, the technology has not always kept up with the performance expectations.

This study explores new modulation and coding techniques to possibly be used in the improvement of the read reliability of RFID systems. Bit and tag error probabilities are computed for various OOK and M-CSK modulation schemes in a varying Nakagami-m fading channel, and the best performing schemes are identified for future employment.

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EXECUTIVE SUMMARY

Radio Frequency Identification (RFID) technology has become a popular technology for use in the logistics environment. The US Department of Defense (DoD) has mandated the use of RFID tags at the pallet and case level for its suppliers. Individual unit tagging remains an issue due to reader errors, tag conflict, orientation of the tag compared to the reader, distance, and other factors.

This study investigates current RFID technology, specifically in the single tag to single reader environment using various coding schemes, power levels, and tag to reader orientations. The goal is to find situations that will increase tag read reliability, leading to greater efficiencies to users of the RFID technology.

The RFID system consists of the tag and the reader. Tags can be active or passive devices, but this study concentrates on the passive tags due to the low cost and high market penetration. RFID readers are made up of a transmitter and a receiver. The transmitter sends out energy at a certain frequency, while the receiver sends the received tag signal to a microprocessor for identification. The reader can be fixed or mobile, with mobile readers usually being handheld. The fixed reader would be mounted near an area that a tagged product would be moving through so it can record the product's identification code as the product is being transported.

The RFID reader and tag do not operate in a perfect environment. Multi-path delays contribute to constructive and destructive interference, which can greatly affect the read reliability of an RFID tag. To model the fading channel properties of the RFID system, the Nakagami-m fading model is used. By varying properties of the equation, the fading model being used can be easily changed from Raleigh, to Rician, to Additive White Gaussian Noise.

Equations for the bit error probabilities of on-off keying (OOK) and M-ary code shift keying (M-CSK) are developed. The two equations are placed into the equation that represents the effect of repetition coding and two uniform distributions are used to average the effects of tag to reader orientation. Finally, the bit error probabilities

computed are then transformed into tag error probabilities with a tag length of 96 bits. The tag error probabilities best display the actual read reliability performance possibilities of an actual RFID tag.

The results show that repetition coding both improves and reduces read performance depending on the fading environment. When the environment resembles the expected real world environment, repetition coding for the most part reduces read reliability.

The best way to increase read reliability performance through coding is to use code shift keying with a high M value. Results show a consistent 4 to 5 dB reduction in signal-to-noise ratio needed to achieve a certain error rate performance level when using 16-CSK compared to OOK.

The overall best way to increase read reliability performance comes from ensuring the best alignment of tag and reader to ensure that the highest possible amount of power can be received.

Future work to further improve RFID technology could include experimenting with a Hamming code in place of the repetition code, since Hamming code works much better in a non-coherent system. Exploring the effects of multiple tags in a single reader interrogation zone, which can lead to tag data collision, could lead to improved deconfliction schemes. Finally, a real world test of various RFID systems to test the actual effects of the fading environment could be helpful to understanding the best modulation scheme to use to increase performance.

I. INTRODUCTION

A. BACKGROUND

Radio Frequency Identification (RFID) technology has become a popular technology for use in the logistics environment. The US Department of Defense (DoD) has mandated the use of RFID tags at the pallet and case level for its suppliers. Individual unit tagging remains an issue due to reader errors, tag conflict, orientation of the tag compared to the reader, distance, and other factors.

RFID systems use radio waves to identify objects over relatively short distances. The advantages include no need for line-of-sight to the object, and quick identification of multiple objects. The disadvantages include distance limitations due to power, cost, and environmental degradation of the signal.

The RFID system consists of the tag and the reader.

1. RFID Tags

RFID tags are manufactured in many shapes and sizes, and each form factor is meant to be used in certain optimum situations. Tags can be active or passive devices. The active devices have an onboard battery, which allows for a greater power output leading to better read reliability. The downside is a much higher cost due to the battery. Passive devices can be much smaller, and use the energy of the reader to reply with its identification string. This study will concentrate on the passive tags, which are in higher demand due to the low cost.

2. RFID Readers

RFID readers are made up of a transmitter and a receiver. The transmitter sends out energy at a certain frequency, while the receiver sends the received tag signal to a microprocessor for identification. The frequency used for transmission can vary depending on the intended use of the RFID system. Frequencies used range from 125

kHz to 5.8 Ghz, where lower frequencies work better in a fading environment but have shorter range and slower data rates then the higher frequency systems. More power is needed for the higher frequency systems, which means the system might require active tags to operate. The advantages include higher data rates and longer read ranges, which may be a sufficient incentive to bear the greater tag cost. The readers can be fixed or mobile, with mobile readers usually being handheld. The fixed reader would be mounted near an area that a tagged product would be moving through so it can record the products identification code as the product is being transported.

B. OBJECTIVE

The objective of this study is to investigate current RFID technology, specifically in the single tag to single reader environment using various coding schemes, power levels, and tag to reader orientations. The goal is to find situations that will increase tag read reliability, leading to greater efficiencies to users of the RFID technology.

C. RELATED WORK

The foundation of this thesis is based on the previous work by Ling Siew Ng, who wrote her thesis in 2006 [1]. In it, she describes in detail how an RFID system works and what main factors affect the read reliability of such a system. She also simulates on-off keying, code shift keying and repetition code systems in Simulink and applies the results to a case study. This study expands on her work in multiple ways which are described in the study methodology.

Other studies dealing with RFID system were found to be mostly based on the testing of current RFID technology, where this study focuses on theoretical tag coding schemes in a fading environment.

D. STUDY METHODOLOGY

This study is focused on the performance of RFID tags in a multi-path fading environment. The Nakagami-m fading model will be used, which can be used to vary the statistical properties of the fading environment.

The focus will be on uni-directional communication between an RFID tag and the reader. The tag will communicate with coded modulation schemes that include non-coherent on-off keying, non-coherent code shift keying, and repetition coding. The orientation of the tag to the reader will be taken into account by using two uniform distributions. The tag error rate is the performance metric that will be used to evaluate the different modulation schemes. The current standard RFID tag size is 96 bits.

This study uses mathematical equations to model the RFID system in the case of tag to reader transmission. The equations are developed by taking the various expressions for the coding schemes, fading channel, and tag error rate and combining them to get equations that can be evaluated for data relevant to this study. The expressions are evaluated with MathCad, and then the resulting data is exported to MATLAB to produce figures for analysis.

E. ORGANIZATION OF THESIS

This chapter is written to give the reader a brief overview of an RFID system. The rest of the thesis is organized as follows: Chapter II presents the various methods that will be utilized to increase the tag reliability rate. Chapter III presents the equations used in the case of on-off keying modulation. Chapter IV presents the equations used in the case of code shift keying modulation. Chapter V presents the numerical results of the study, with plots representing different situations. Chapter VI presents the performance analysis, conclusions of the study and provides ideas for future work.

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II. METHODS TO INCREASE READ RELIABILITY

A. MODULATED BACKSCATTER

Passive RFID tags communicate with the reader through modulated backscattering of the transmitted reader signal. This mode of communication allows the tag to use the power of the reader to send its identification signal out.

The tag antenna is tuned to the reader frequency due to its inherent size and shape. The tag changes the reflection properties of itself by turning a set amount of impedance on and off, this creates the signal modulation that allows for bits to be sent [2]. The identification signal is sent back to the reader through the modulation of the reflection of the initial transmitted signal. This is where the modulated backscatter mode of communication gets its name.

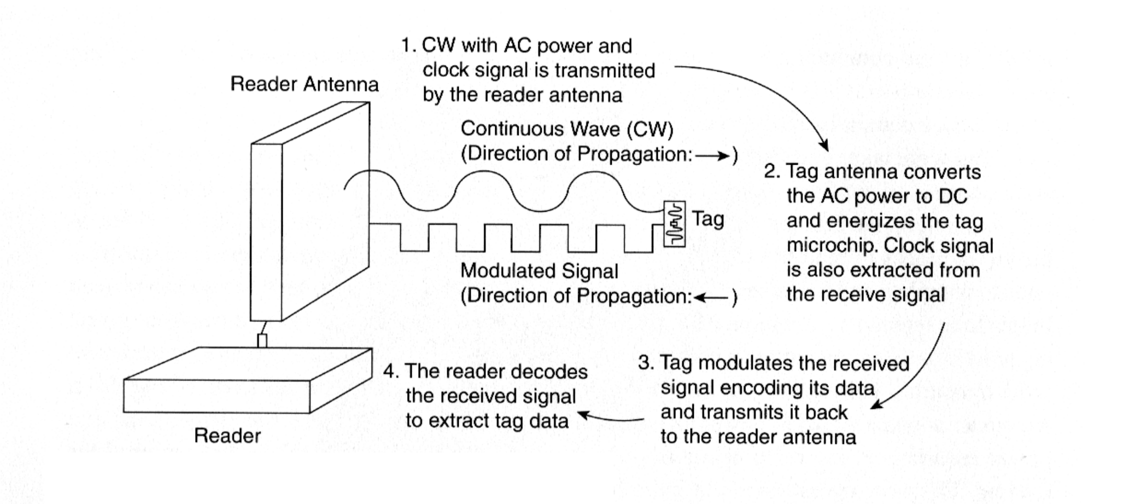

Figure 1. RFID Reader and Tag Communication Chain (from [3])

The reflection of the signal is not necessarily straight back to the reader, it can be scattered in all directions. This causes problems with the reader due to the multi-path effects, and lower received power.

The modulation technique used has a great effect on the read reliability of the tag. This study examines the effects of using on-off keying, code shift keying, and repetition coding to increase the read reliability of the RFID tag in a fading environment.

B. NAKAGAMI-M FADING MODEL

The reader and tag do not operate in a perfect environment. Multi-path delays contribute to constructive and destructive interference which can greatly affect the read reliability of an RFID tag. To model the fading channel properties of the RFID system, the Nakagami-m fading model will be used. By varying properties of the equation, the fading model being used can be easily changed from Raleigh, to Rician, to Additive White Gaussian Noise.

The probability density function of the Nakagami-m fading channel is equal to:

$$f_R(r) = \frac{2m^m r^{2m-1}}{\left(2\sigma^2\right)^m \Gamma(m)} e^{\frac{-mr^2}{2\sigma^2}}, \; r \geq 0 \tag{1}$$

where m determines the type of fading environment, $\Gamma(m)$ is a gamma function, r^2 is the instantaneous energy per symbol (that is, r is the instantaneous amplitude of a symbol), and σ^2 is the mean square value of r [4]. When m is equal to one the multi-path fading is a Raleigh fading model. When m is above one, the fading environment more closely resembles a Rician model. The larger m becomes, the greater the line-of-sight signal power is assumed to be. The m value corresponds to the k value used in the Rician fading model by using the following equation:

$$m = \frac{\left(k+1\right)^2}{\left(2k+1\right)}, \tag{2}$$

where k describes the ratio of line-of-sight to diffuse signal power. In this study, a reasonable real world environment might range from $k=8$ to $k=100$ which corresponds to m values of about 5 and 50, respectively.

The Nakagami-m probability density function is discussed in greater detail in the Appendix.

C. CODING TECHNIQUES FOR INCREASED PERFORMANCE

One of the ways to increase RFID read reliability is to change the method of tag modulation. Most tags used today only use simple on-off keying, where the signal is ON for a 1 bit and OFF for a 0 bit. This allows for a very simple tag but has limitations in its effectiveness. Two coding techniques, Code Shift Keying and repetition coding are explored in this study. The goal is to increase error probability performance over that of basic on-off keying.

1. Code Shift Keying

Code shift keying uses a set of $M = 2^k$ orthogonal sinusoidal Walsh functions to represent a set of M distinct k-bit symbols where M is a power of 2 [1]. Walsh functions consist of orthogonal square pulses with only the allowed states of 1 and -1. The Walsh function and can be obtained from the Hadamad matrix given by

$$H_M = \begin{bmatrix} H_{M/2} & H_{M/2} \\ H_{M/2} & -H_{M/2} \end{bmatrix}$$

The Walsh function when $M = 4$ can be obtained recursively as follows

$$H_1 = 1$$

$$H_2 = \begin{bmatrix} H_1 & H_1 \\ H_1 & -H_1 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$H_4 = \begin{bmatrix} H_2 & H_2 \\ H_2 & -H_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

Figure 2 shows how a CSK modulator maps the input bits to the corresponding Walsh function, then modulates the function by the carrier signal to create the CSK signal.

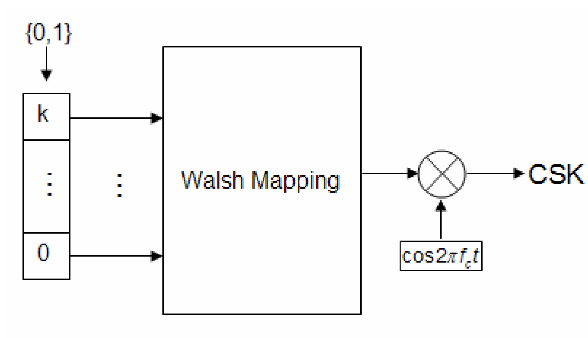

Figure 2. CSK Modulator (from [1])

For example, to transmit the two bit data sequence [0 1] the data will be transformed into four Walsh function chips. The resulting coded sequence would be

[1 -1 1 -1] as can be seen below in Figure 3.

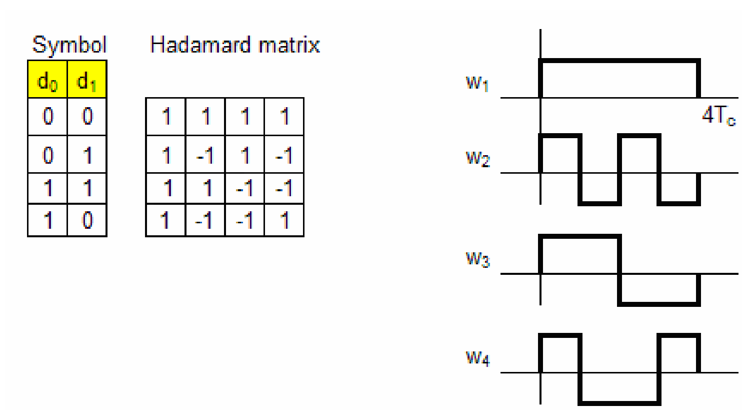

Figure 3. Walsh Functions when M = 4 for CSK (from [1])

A 4-ary Walsh function has four unique code words that represent the four possible combinations of the two data bits. If the sequence that is received does not match one of the four possibilities, the demodulator is usually able to determine which of these four were actually transmitted by using a maximum detector. This technique is

known as hard-decision demodulation. If a larger M value is used, which means more unique symbols are used, the performance of the hard-decision demodulation is increased [4].

2. Repetition Coding

Repetition coding is one of the simplest error correction codes available for use. Instead of only sending a data bit once, a repetition coding scheme sends n copies of the data bit. The n copies must be an odd integer value, because the receiver adds up the number of ones and number of zero bits. The highest total of received bits is assumed to be the correct data bit. This technique can greatly reduces the bit error rate in certain situations.

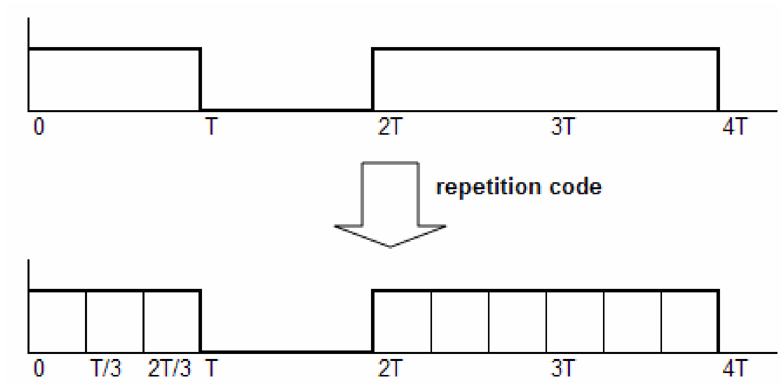

Figure 4. Original data stream versus Repetition Coding of n = 3 (from [1])

The coded bit stream coming from the repetition coder has a data rate n times higher than the input data stream. This means that even though the data bits are repeated n times as coded bits, the actual data bit rate is not reduced. Figure 4 shows the repeated bits occurring in the same amount of time as the input data bit. The main disadvantage of the repetition coding technique is the increase in the necessary bandwidth, which is n times larger then the no repetition coding case.

Figure 5 shows the reduction of the bit error rate as the number of repetitions is increased. The bit in this example has a bit error probability of 0.5.

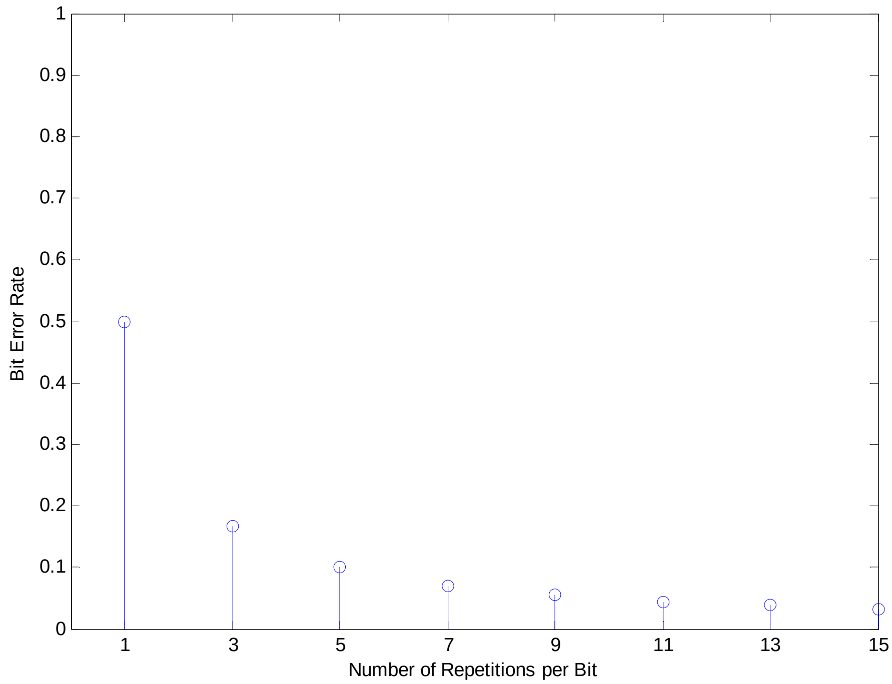

Figure 5. Bit Error Probabilities for various levels of repetition coding

The figure shows that there is a 66% reduction in the bit error probability when going from no repetition to three repetitions of the data bit. As the initial bit error probability falls, the corresponding repetition bit error probabilities decrease at even higher rates. For example, if the initial bit error probability is 0.1, the reduction in BER when there are three repetitions is about 90%. The equation that expresses the error probability for different repetition values follows [5]:

$$P_e(n) = \sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} \left[1 - P_b\right]^{n-k} P_b^{\,k} \qquad (3)$$

where n is the number of times the data bit is repeated, and P_b is the initial bit error probability.

Equation (3) is used later in Chapters III and IV to help create the test equations for this study.

D. TAG ERROR PROBABILITY

An RFID tag consists of a string of bits, with certain bits corresponding to company codes, serial numbers and other identifying information. A standard RFID tag consists of 96 bits. For a tag to be read successfully, all of the bits must be properly decoded. This study will investigate the tag error probabilities instead of the bit error probabilities, since the goal is to increase the reliability of a tag read.

The equation used to find the tag error probability from the bit error probability is as follows:

$$P_{T,e} = 1 - \left(1 - P_b\right)^N \tag{4}$$

where P_b is the bit error probability and N is the number of bits in the tag. In Figure 6 below, the tag error probability is plotted using a P_b of 0.1. The number of bits in the tag increases to the right. As the number of bits in the tag increases so does the tag error probability, due to the fact that longer tags means the probability of all bits being received correctly becomes lower.

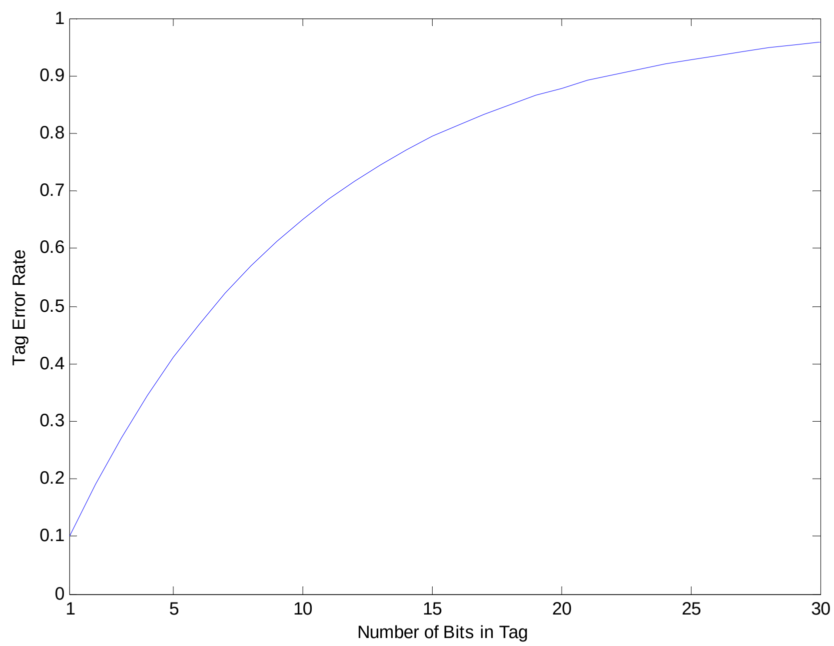

Figure 6. Tag Error Probability for various number of bits with a Bit Error Probability of 0.1

E. ORIENTATION OF TAG TO READER

The orientation of the tag to the reader affects the read reliability of the RFID system. When the tag and reader are perfectly aligned, the received power is maximized, which in turn minimizes the tag error probability. As the tag and reader become misaligned, the performance is reduced, due to the reduction of the received power. The power loss is due to the fact that the tag and reader are not aligned down each others boresights.

The Friis transmission formula can be used to quantify the lost power due to misalignment. The received power P_r is calculated by equation (5) which is determined by the wavelength λ of the signal, the distance d between the two antennas, and the power transmitted, P_t.

$$P_r = \frac{A_{et} A_{er}}{d^2 \lambda^2} P_t \tag{5}$$

where the apertures of the two antennas are

$$\begin{aligned} A_{er} &= k_r \cos^2 \theta \\ A_{et} &= k_t \end{aligned} \tag{6}$$

The two k values are constants associated with the antenna characteristics for both the transmit and receive antennas. The angle θ is the angle between the reader orientation and the propagating wave front from the tag [1].

Since the k values are constant the power loss due to orientation can be described by $\cos^2 \theta$. In Figure 7, the normalized received power is shown verses the angle of orientation from the tag to the reader. When misaligned by 45 degrees the received power is cut in half, while at 90 degrees misaligned the received power is zero.

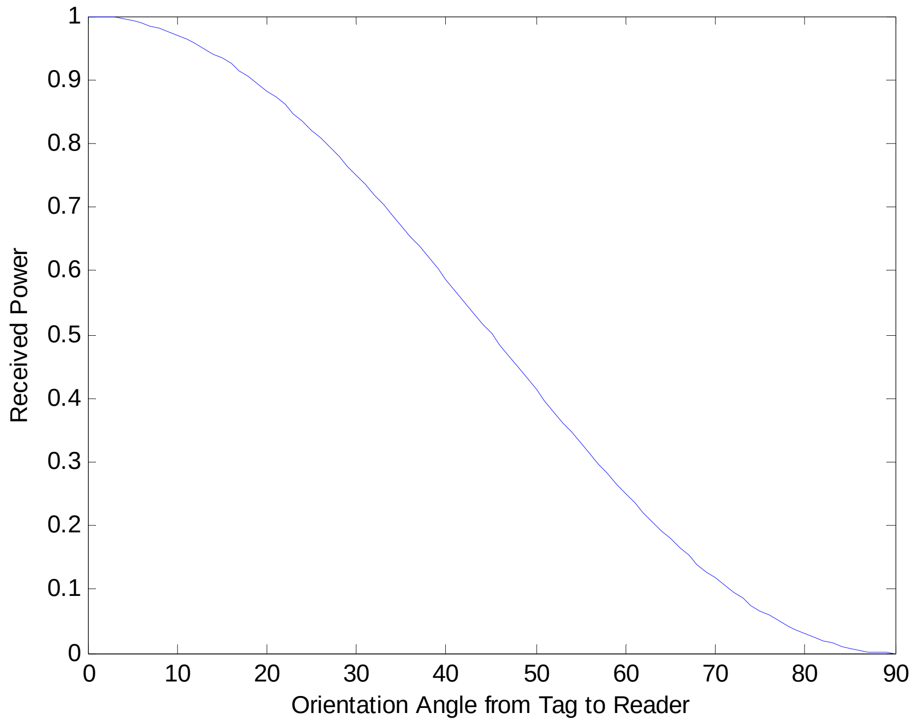

Figure 7. Expected Received Power verses Orientation Angle for RFID Tag

In order to account for this real world fact of misalignment, a probability distribution needs to be utilized. The actual orientation of thousands of tags would be impossible to calculate, but a distribution for θ can be used to estimate the tag error probability that can be used in the model. In this study, two uniform distributions will be used. The first will be from $p(\theta)=\frac{1}{\pi}\begin{cases} -\pi/2 \le \theta \le \pi/2 \\ 0 \text{ elsewhere} \end{cases}$, and the second will be from $p(\theta)=\frac{2}{\pi}\begin{cases} -\pi/4 \le \theta \le \pi/4 \\ 0 \text{ elsewhere} \end{cases}$. Even the second distribution could be pessimistic, especially in the case of a hand held reader. Further discussion of the uniform distributions used can be found in Chapter III.

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III. ON-OFF KEYING (OOK)

The first modulation scheme being studied is the one that most RFID tags use today, non-coherent on-off keying. The reason it is used is its simplicity, which allows for cheap manufacturing of tags and simple receivers.

An OOK signal is either transmitting a sine wave which represents a data bit 1, or not transmitting, which represents a data bit 0. This modulation scheme is quite common, and because of that there are equations that describe the bit error probability of such a scheme.

This chapter will cover the derivation of the complete equation used to study the tag error probabilities of an OOK-based RFID system with different coding schemes in a multitude of fading environments.

A. OOK BIT ERROR PROBABILITY

The equation describing the probability of bit error for an OOK modulation scheme is [6],

$$P_b = \frac{1}{2} e^{-\frac{E_b}{2N_o}} \tag{7}$$

where $\frac{E_b}{N_o}$ is the signal-to-noise ratio.

Equation (7) will be used as a comparison tool to check the results of the fading channel equation which is worked out in the next section.

B. OOK IN NAKAGAMI-M CHANNEL

The Nakagami-m fading channel probability density function that was seen earlier as equation (1) is then multiplied by the OOK bit error probability equation, which is equation (7). The multiplied terms must then be integrated to find a closed form expression for the bit error probability, P_b.

$$P_b = \int_0^\infty P_b(r) f_R(r) dr \tag{8}$$

where r^2 replaces E_b in a fading channel. Direct integration of equation (8) yields the bit error probability of an OOK signal in a Nakagami-m fading channel, which is given as

$$P_b = \frac{1}{2}\left(\frac{2m}{2m + \frac{E_b}{N_o}}\right)^m, \quad \frac{1}{2} \le m \le \infty \tag{9}$$

C. ORIENTATION ANGLE

To account for the orientation of the tag to the reader the $\cos^2\theta$ factor is incorporated into the signal-to-noise ratio per bit:

$$P_b(\theta) = \frac{1}{2}\left(\frac{2m}{2m + \frac{E_b}{N_o}\cos^2\theta}\right)^m \tag{10}$$

D. REPETITION CODING

The repetition code discussed earlier is now used to test the effects of repetition coding with OOK in the fading environment:

$$P_b(n,\theta) = \sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} \left[1 - P_b(\theta)\right]^{n-k} [P_b(\theta)]^k \tag{11}$$

The repetition code repeats the data bit n times in the same amount of time as the original bit would be transmitted. Because of this, the initial bit energy is spread out over

each n bit in the repetition code. Thus with repetition code, the coded bit energy-to-noise ratio is:

$$\frac{E_c}{N_o} = \frac{1}{n}\frac{E_b}{N_o} \tag{12}$$

Substituting equations (10) and (12) into equation (11) yields the coded bit error probability:

$$P_b(n,\theta) = \sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} \left[1 - \frac{1}{2}\left(\frac{2m}{2m + \frac{E_b}{nN_o}\cos^2\theta} \right)^m \right]^{n-k} \left[\frac{1}{2}\left(\frac{2m}{2m + \frac{E_b}{nN_o}\cos^2\theta} \right)^m \right]^k \tag{13}$$

E. UNIFORM DISTRIBUTION

To find the tag error probability with an unknown tag orientation, a probability distribution can be utilized. For the purposes of this study, two uniform distributions have been selected. The first distribution gives an equal chance for all orientation angles from -90° to 90° to occur:

$$f_\theta(\theta) = \frac{1}{\pi},\ \frac{-\pi}{2} \le \theta \le \frac{\pi}{2} \tag{14}$$

The second distribution gives an equal chance for all orientation angles from -45° to 45° to occur:

$$f_\theta(\theta) = \frac{2}{\pi},\ \frac{-\pi}{4} \le \theta \le \frac{\pi}{4} \tag{15}$$

The distribution then placed into equation (13) to yield the average bit error probability:

$$P_b(n) = \mathbf{E}\left[P_b(n,\theta)\right] = \int_{-\infty}^{\infty} P_b(n,\theta) f_\theta(\theta)\, d\theta \tag{16}$$

This results in the two equations for the respective distributions:

$$P_{b,\pi/2}(n) = \frac{1}{\pi}\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}} \sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} \left[1-\frac{1}{2}\left(\frac{2m}{2m+\frac{E_b}{nN_o}\cos^2\theta}\right)^m\right]^{n-k} \left[\frac{1}{2}\left(\frac{2m}{2m+\frac{E_b}{nN_o}\cos^2\theta}\right)^m\right]^k d\theta \quad (17)$$

and,

$$P_{b,\pi/4}(n) = \frac{2}{\pi}\int_{\frac{-\pi}{4}}^{\frac{\pi}{4}} \sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} \left[1-\frac{1}{2}\left(\frac{2m}{2m+\frac{E_b}{nN_o}\cos^2\theta}\right)^m\right]^{n-k} \left[\frac{1}{2}\left(\frac{2m}{2m+\frac{E_b}{nN_o}\cos^2\theta}\right)^m\right]^k d\theta \quad (18)$$

F. TAG ERROR PROBABILITY

To obtain the tag error probability, equation (4) is utilized:

$$P_{T,e} = 1-\left[1-P_b(n)\right]^N$$

The variable N is equal to the number of data bits per tag. Since the standard RFID tag has 96 bits, N is equal to 96. It is important to note that when repetition coding is used, the packet size for the 96 data bits is increased. For repetition of $n=3$, the coded bit length would be $96\times 3 = 288$ coded bits. This triples the needed bandwidth due to the increase in data rate. Placing equations (17) and (18) respectively into the $P_b(n)$ yields:

$$P_{T,e,\pi/2} = 1-\left[1-P_{b,\pi/2}(n)\right]^N \quad (19)$$

And,

$$P_{T,e,\pi/4} = 1-\left[1-P_{b,\pi/4}(n)\right]^N \quad (20)$$

IV. CODE SHIFT KEYING (CSK)

The second modulation scheme being studied is M-ary code shift keying. The increased complexity of the coding for each data bit allows for lower bit error probabilities. CSK is not currently used in an RFID tag, but this study is meant to explore the performance possibilities.

This chapter will cover the derivation of the complete equation used to study the tag error probabilities of a non-coherent M-CSK-based RFID system with different coding schemes in a multitude of fading environments.

A. CSK BIT ERROR PROBABILITY IN NAKAGAMI-M CHANNEL

The equation representing the symbol error probability of non-coherent M-ary orthogonal signals is as follows:

$$P_e = \sum_{k=1}^{M-1} \binom{M-1}{k} (-1)^{k+1} \frac{1}{k+1} e^{-\left[\frac{k}{k+1}\right]\frac{E_s}{N_0}} \tag{21}$$

The conditional symbol error probability, $P_e(r)$, of non-coherent M-ary orthogonal signals is obtained by replacing E_s with r^2 where r is a value assumed by Nakagami-m random variable. It is calculated as

$$P_e(r) = \sum_{k=1}^{M-1} \binom{M-1}{k} (-1)^{k+1} \frac{1}{k+1} e^{-\left[\frac{k}{k+1}\right]\frac{r^2}{N_0}} \tag{22}$$

where

$$E_s = E\left[r^2\right] = 2\sigma^2 \tag{23}$$

[4].

The goal is to place the CSK modulation symbol error probability into the Nakagami-m fading channel and get a closed form expression. To do this the CSK

symbol error probability, equation (22), must be multiplied by the probability density function of the Nakagami-m model, equation (1). Then the product must be integrated over all amplitude levels:

$$P_e = \int_0^\infty P_e(r) f_R(r) dr \tag{24}$$

The result follows with the constants brought outside the integral:

$$P_e = \sum_{k=1}^{M-1} \binom{M-1}{k} (-1)^{k+1} \frac{1}{k+1} \int_0^\infty \left[e^{-\left[\frac{k}{k+1}\right]\frac{r^2}{N_o}} \right] \left(\frac{2m^m r^{2m-1}}{\left(2\sigma^2\right)^m \Gamma(m)} e^{\frac{-mr^2}{2\sigma^2}} \right) dr \tag{25}$$

Next, concentrating only on the integration part of the equation

$$\int_0^\infty \left(\frac{2m^m r^{2m-1}}{\left(2\sigma^2\right)^m \Gamma(m)} \right) \left[e^{\frac{-mr^2}{2\sigma^2} + \left[\frac{-k}{k+1}\right]\frac{r^2}{N_o}} \right] dr \tag{26}$$

Factoring $\frac{m}{2\sigma^2}$ out of the exponential:

$$\frac{2m^m}{\left(2\sigma^2\right)^m \Gamma(m)} \int_0^\infty r^{2m-1} \left[e^{\frac{-mr^2}{2\sigma^2}\left[1 + \frac{k}{m(k+1)} \frac{2\sigma^2}{N_o}\right]} \right] dr \tag{27}$$

Then using the integration by substitution technique where $u = r^2$ and $du = 2rdr$. Using those substitution values allows for the following,

$$\begin{gathered} rdr = \frac{du}{2} \\ r^{2m-1} dr = r\left(r^{2m-2}\right) dr = r\left(r^{2(m-1)}\right) dr \end{gathered} \tag{28}$$

Substituting $u = r^2$ into equation (28), yields

$$r^{2m-1}dr = u^{m-1}\frac{du}{2} \tag{29}$$

which can then be applied to equation (27) to yield

$$\frac{2m^m}{2\left(2\sigma^2\right)^m\Gamma(m)}\int_0^\infty u^{m-1}\left[e^{\frac{-mu}{2\sigma^2}\left[1+\frac{k}{m(k+1)}\frac{2\sigma^2}{N_o}\right]}\right]du \tag{30}$$

To continue the integration, the following integration identity is used [7],

$$\int_0^\infty x^n e^{-\mu x}dx = n!\mu^{-n-1} \qquad \left[\operatorname{Re}\ \mu > 0\right] \tag{31}$$

where each variable is represented by

$$\begin{aligned} &x = u,\ n = m-1, \\ &\mu = \frac{m}{2\sigma^2}\left[1+\frac{k}{m(k+1)}\frac{2\sigma^2}{N_o}\right] \end{aligned} \tag{32}$$

Completing the identity substitution results in

$$\frac{2m^m}{2\left(2\sigma^2\right)^m\Gamma(m)}\left[(m-1)!\left(\frac{m}{2\sigma^2}\right)^{-m}\left[1+\frac{k}{m(k+1)}\frac{2\sigma^2}{N_o}\right]^{-m}\right] \tag{33}$$

Simplification is then possible because of the fact that for integer *m*

$$\Gamma(m) = (m-1)! \tag{34}$$

So the equation simplifies to

$$\left[1+\frac{k}{m(k+1)}\frac{2\sigma^2}{N_o}\right]^{-m} \tag{35}$$

Replacing the integration in equation (25), with the integrated result of equation (35) yields

$$P_e=\sum_{k=1}^{M-1}\binom{M-1}{k}(-1)^{k+1}\frac{1}{k+1}\left[1+\frac{k}{m(k+1)}\frac{E_s}{N_o}\right]^{-m} \tag{36}$$

where $2\sigma^2=E_s$ as seen in equation (23). Finally, to find the bit error probability instead of the symbol error probability the following equations are utilized

$$E_s=E_b\log_2 M \tag{37}$$

$$P_b=\frac{M/2}{M-1}P_e \tag{38}$$

which yields a final equation of

$$P_b=\frac{M/2}{M-1}\sum_{k=1}^{M-1}\binom{M-1}{k}(-1)^{k+1}\frac{1}{k+1}\left[1+\frac{k}{m(k+1)}\frac{E_b}{N_o}\log_2 M\right]^{-m} \tag{39}$$

Equation (39) represents the M-ary CSK bit error probability in a Nakagami-m fading channel, where *m* is an integer. Note that when $M=2$, equation (39) is equal to the OOK bit error probability shown in equation (9).

B. ORIENTATION ANGLE

To account for the angle of orientation θ from the tag to the reader, the transmitted power must be multiplied by $\cos^2\theta$:

$$P_b(\theta) = \frac{M/2}{M-1}\sum_{k=1}^{M-1}\binom{M-1}{k}(-1)^{k+1}\frac{1}{k+1}\left[1+\frac{k}{m(k+1)}\frac{E_b}{N_o}(\log_2 M)\cos^2\theta\right]^{-m} \qquad (40)$$

C. REPETITION CODING

The repetition code discussed earlier is now used to test the effects of repetition coding with CSK in the fading environment:

$$P_b(n,\theta) = \sum_{k=\frac{n+1}{2}}^{n}\binom{n}{k}\left[1-P_b(\theta)\right]^{n-k}[P_b(\theta)]^k \qquad (41)$$

The repetition code repeats the data bit n times in the same amount of time as the original bit would be transmitted. Because of this, the initial bit energy is spread out over each n bit in the repetition code. Thus with repetition code, the coded bit energy-to-noise ratio is:

$$\frac{E_c}{N_o} = \frac{1}{n}\frac{E_b}{N_o} \qquad (42)$$

Substituting equations (40) and (42) into equation (41) yields the coded bit error probability:

$$P_b(n,\theta) = \sum_{k=\frac{n+1}{2}}^{n}\binom{n}{k}\left[1-\frac{M/2}{M-1}\sum_{k=1}^{M-1}\binom{M-1}{k}(-1)^{k+1}\frac{1}{k+1}\left[1+\frac{k}{m(k+1)}\frac{E_b}{nN_o}(\log_2 M)\cos^2\theta\right]^{-m}\right]^{n-k}\times$$
$$\left[\frac{M/2}{M-1}\sum_{k=1}^{M-1}\binom{M-1}{k}(-1)^{k+1}\frac{1}{k+1}\left[1+\frac{k}{m(k+1)}\frac{E_b}{nN_o}(\log_2 M)\cos^2\theta\right]^{-m}\right]^{k} \qquad (43)$$

D. UNIFORM DISTRIBUTION

To find the tag error probability with an unknown tag orientation, a probability distribution can be utilized. For the purposes of this study, two uniform distributions have been selected. The first distribution gives an equal chance for all orientation angles from -90° to 90° to occur

$$f_\theta(\theta) = \frac{1}{\pi}, \quad \begin{cases} \frac{-\pi}{2} \le \theta \le \frac{\pi}{2} \\ 0 \text{ elsewhere} \end{cases} \tag{44}$$

The second distribution gives an equal chance for all orientation angles from -45° to 45° to occur

$$f_\theta(\theta) = \frac{2}{\pi}, \quad \begin{cases} \frac{-\pi}{4} \le \theta \le \frac{\pi}{4} \\ 0 \text{ elsewhere} \end{cases} \tag{45}$$

The distribution then placed into equation (43) to yield the average bit error probability

$$P_b(n) = \mathbf{E}\left[P_b(n,\theta)\right] = \int_{-\infty}^{\infty} P_b(n,\theta) f_\theta(\theta)\, d\theta \tag{46}$$

This results in the two equations for the respective distributions

$$P_{b,\pi/2}(n) = \frac{1}{\pi} \int_{\frac{-\pi}{2}}^{\frac{\pi}{2}} \begin{array}{l} \displaystyle\sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} \left[1 - \frac{M/2}{M-1} \sum_{k=1}^{M-1} \binom{M-1}{k} (-1)^{k+1} \frac{1}{k+1} \left[1 + \frac{k}{m(k+1)} \frac{E_b}{nN_o} (\log_2 M) \cos^2\theta \right]^{-m} \right]^{n-k} \times \\ \displaystyle \left[\frac{M/2}{M-1} \sum_{k=1}^{M-1} \binom{M-1}{k} (-1)^{k+1} \frac{1}{k+1} \left[1 + \frac{k}{m(k+1)} \frac{E_b}{nN_o} (\log_2 M) \cos^2\theta \right]^{-m} \right]^{k} d\theta \end{array} \tag{47}$$

and,

$$P_{b,\pi/4}(n) = \frac{2}{\pi}\int_{\frac{-\pi}{4}}^{\frac{\pi}{4}} \frac{\displaystyle\sum_{k=\frac{n+1}{2}}^{n}\binom{n}{k}\left[1-\frac{M/2}{M-1}\sum_{k=1}^{M-1}\binom{M-1}{k}(-1)^{k+1}\frac{1}{k+1}\left[1+\frac{k}{m(k+1)}\frac{E_b}{nN_o}(\log_2 M)\cos^2\theta\right]^{-m}\right]^{n-k}\times}{\left[\displaystyle\frac{M/2}{M-1}\sum_{k=1}^{M-1}\binom{M-1}{k}(-1)^{k+1}\frac{1}{k+1}\left[1+\frac{k}{m(k+1)}\frac{E_b}{nN_o}(\log_2 M)\cos^2\theta\right]^{-m}\right]^{k} d\theta} \tag{48}$$

E. TAG ERROR PROBABILITY

To obtain the tag error probability, equation (4) is utilized

$$P_{T,e} = 1-\left[1-P_b(n)\right]^N \tag{49}$$

The variable N is equal to the number of data bits per tag. Since the standard RFID tag has 96 bits, N is equal to 96. It is important to note that when repetition coding is used, the packet size for the 96 data bits is increased. For repetition of $n = 3$, the coded bit length would be $96\times 3 = 288$ coded bits. This triples the needed bandwidth due to the increase in data rate. Placing equations (47) and (48) respectively into the $P_b(n)$ in equation (49) yields:

$$P_{T,e,\pi/2} = 1-\left[1-P_{b,\pi/2}(n)\right]^N \tag{50}$$

and,

$$P_{T,e,\pi/4} = 1-\left[1-P_{b,\pi/4}(n)\right]^N \tag{51}$$

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V. NUMERICAL RESULTS

To compute the data used in the following figures, equations (13), (47), (48), (50) and (51) were used. The equations were evaluated using MathCAD, and the results were transferred to MATLAB to plot [8][9].

Within the different equations used for the figures, there are four main variables that describe the fading environment and the coding-modulation scheme that was used. N is the number of data bits per tag; m determines the Nakagami-m fading environment; M is the value of the M-ary CSK; and n is the number of times the data bit is repeated for the repetition coding. Additionally, the uniform distribution can be from $\frac{-\pi}{2}$ to $\frac{\pi}{2}$ or $\frac{-\pi}{4}$ to $\frac{\pi}{4}$.

While many plots were constructed to further understand the behavior of the different coding-modulation schemes in each fading environment, only the most noteworthy plots are included.

A. DATA ANALYSIS

Figure 8 shows the different bit error probability results for various fading channel environments. As the value of *m* rises, which corresponds to the ratio of line-of-sight power to diffuse power, the bit error probability becomes better. This is due to the fact that line-of-sight signal transmission is much more efficient and easier to decode accurately.

The bit error probability results for the OOK modulation scheme in a Nakagami-m fading channel with repetition coding presented in Figures 9 through 12 are important for a few reasons.

First, the bit error probability varies greatly depending on the amount of power delivered by line-of-sight. Figure 9 shows $E_b/N_o = 30dB$ at $P_b = 10^{-3}$ when $m = 1$,

while Figure 12 shows $E_b/N_o = 12dB$ at $P_b = 10^{-3}$ when $m = 20$. That means there is about an 18 dB reduction in signal-to-noise ratio needed to achieve $P_b = 10^{-3}$ for OOK when $m = 20$ compared to when $m = 1$.

Second, the effect of repetition coding on the non-coherent OOK signal is not always constant. Figure 9 shows repetition coding reduces the signal-to-noise ratio needed to achieve $P_b = 10^{-3}$ by 16 dB when $m = 1$. Figure 12 shows repetition coding actually increases the signal-to-noise ratio needed to achieve $P_b = 10^{-3}$ by 2 dB when $m = 20$.

There is a certain signal-to-noise ratio in each figure where the repetition coding starts to increase performance. Figure 9 shows that point to be $E_b/N_o = 6dB$ when $m = 1$. Figure 10 shows the crossover point at $E_b/N_o = 8.5dB$ when $m = 2$. Figure 11 shows the crossover point at $E_b/N_o = 12dB$ when $m = 5$. Figure 12 shows that the crossover point either never occurs or is so high in signal-to-noise ratio required as to be useless. The degradation of the repetition code performance benefit is due to non-coherent combining loss [4].

Figures 13 through 17 show the bit error probability for various M-CSK schemes and fading channel situations. Figure 13 shows the bit error probability for a non-coherent M-CSK receiver with m = 5, M = 2, 4, 8, 16, n = 1 and a uniform distribution from $\frac{-\pi}{2}$ to $\frac{\pi}{2}$. Figure 13 shows the bit error probability at $E_b/N_o = 30dB$ being no better then $P_b = 10^{-2}$, which is not a very usable bit error rate. This more pessimistic uniform distribution yields a basically unusable error rate, so next the more reasonable distribution is examined.

Figures 14 and 15 show the bit error probability for a non-coherent M-CSK receiver with m = 5, M = 2, 4, 8, 16, a uniform distribution from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$, and n = 1, 3 respectively. Figure 14 shows that using the more reasonable distribution yields an

acceptable bit error probability of $P_b = 10^{-5}$ around signal-to-noise ratios of 16 to 20 dB, depending on the level of code shift keying used.

The performance improvement due to the code shift keying is consistent in Figure 14 and 15. For example, Figure 14 shows that to produce a bit error probability of $P_b = 10^{-5}$ the required signal-to-noise ratios are different for each M value. When $M = 2$, which is an OOK signal, the required $E_b/N_o = 20.5dB$. When $M = 4,\ 8,\ \text{and}\ 16$, then $E_b/N_o = 17.5dB, 16dB,\ \text{and}\ 15.25dB$ respectively. This shows that there is an initial 3 dB performance improvement that can be attributed to CSK when $M = 4$. Additional gains of about 1 dB each can be had if CSK complexity is increased. This performance gain from CSK modulation stays quite consistent throughout the rest of the figures which shows that different fading environments don't affect the performance gains had from utilizing CSK.

The performance of repetition coding with both the OOK and CSK signals is consistent with the results found in Figures 9 through 12. Figures 14 and 15 show that when $m = 5$, which is the most realistic real world scenario, the improvement from repetition coding is mixed. Figure 14 shows that for $M = 4$ when $P_b = 10^{-2}$ then $E_b/N_o = 10dB$, and in Figure 15 for $M = 4$, and $n = 3$ when $P_b = 10^{-2}$ then $E_b/N_o = 11dB$ which is a decrease in performance. Then Figure 14 shows that for $M = 4$ when $P_b = 10^{-5}$ then $E_b/N_o = 18dB$, and in Figure 15 for $M = 4$, and $n = 3$ when $P_b = 10^{-5}$ then $E_b/N_o = 17dB$ which is a increase in performance. All this shows that with lower signal-to-noise ratios the repetition coding reduces performance, while at higher ratios there is improved performance. The exact crossover point due to the non-coherent combining is illustrated well by Figure 11.

Figures 16 and 17 show the bit error probability for a non-coherent M-CSK receiver with m = 1, M = 2, 4, 8, 16, a uniform distribution from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$, and n = 1, 3 respectively. The comparison of the two figures show the performance improvement of repetition coding at nearly all signal-to-noise ratios when $m = 1$. This is in contrast to the

earlier case when $m = 5$ and the performance improvement was mixed. Again, the difference relating to repetition coding between the two fading environments is best seen with Figures 9 and 11.

To assess the performance of actual RFID tags, the bit error probabilities were used to compute tag error probabilities where the tag length is set at 96 bits. Figures 18 through 22 show the tag error probabilities for various M-CSK schemes and fading channel situations.

Figures 18 and 19 show the tag error probability for a non-coherent M-CSK receiver with m = 1, M = 2, 4, 8, 16, a uniform distribution from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$, and n = 1, 3 respectively. Figure 18 shows that when $M = 4$ and $m = 1$ to achieve a tag error probability of $P_{T,e} = 0.1$ requires $E_b/N_o = 28dB$. Figure 19 shows that when repetition coding is used then $E_b/N_o = 21dB$ to reach $P_{T,e} = 0.1$. This shows that there is a 7 dB reduction in signal-to-noise ratio needed to achieve a tag error probability of 0.1 when $m = 1$ and repetition coding is used. Additionally, the positive effects of the CSK modulation over the OOK modulation remains the same at 3 to 5 dB as in the earlier cases dealing with the bit error probabilities.

Figures 20 and 21 show the tag error probability for a non-coherent M-CSK receiver with m = 5, M = 2, 4, 8, 16, a uniform distribution from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$, and n = 1, 3 respectively. In the more realistic case where $m = 5$, Figures 20 and 21 show that repetition coding decreases tag error probability performance by a little over 1 dB at all reasonable signal-to-noise ratios. The crossover point where repetition coding starts to increase performance doesn't occur until $E_b/N_o = 12.5dB$ when $m = 5$, and the tag error probability is already well under 0.1 by that time as seen in Figure 20. That means that by the time the repetition coding helps, the reliability of the tag is already at a usable level.

Figure 22 shows the tag error probability for a non-coherent M-CSK receiver with m = 5, M = 2, 4, 8, 16, n = 1 and a uniform distribution from $\frac{-\pi}{2}$ to $\frac{\pi}{2}$. Figure 22 shows that whenever the more pessimistic distribution is used, the tag error probability never gets to a usable level no matter the fading environment, or modulation scheme used. When $E_b/N_o = 30dB$ and $M = 16$, the best tag error probability is still only 0.6 which means that over half the time the tag information returned will be in error.

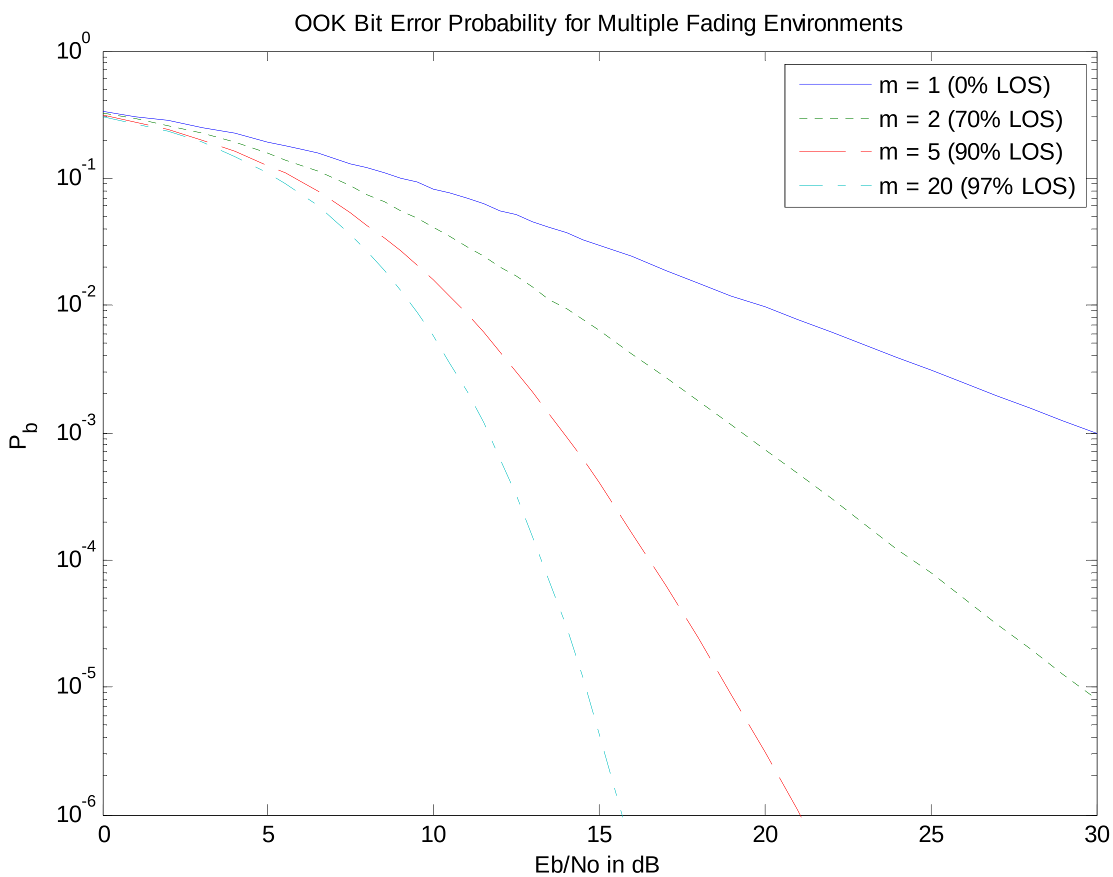

Figure 8. Bit Error Probability Performance for Non-Coherent OOK in various Fading Environments where m = 1, 2, 5, and 20 respectively.

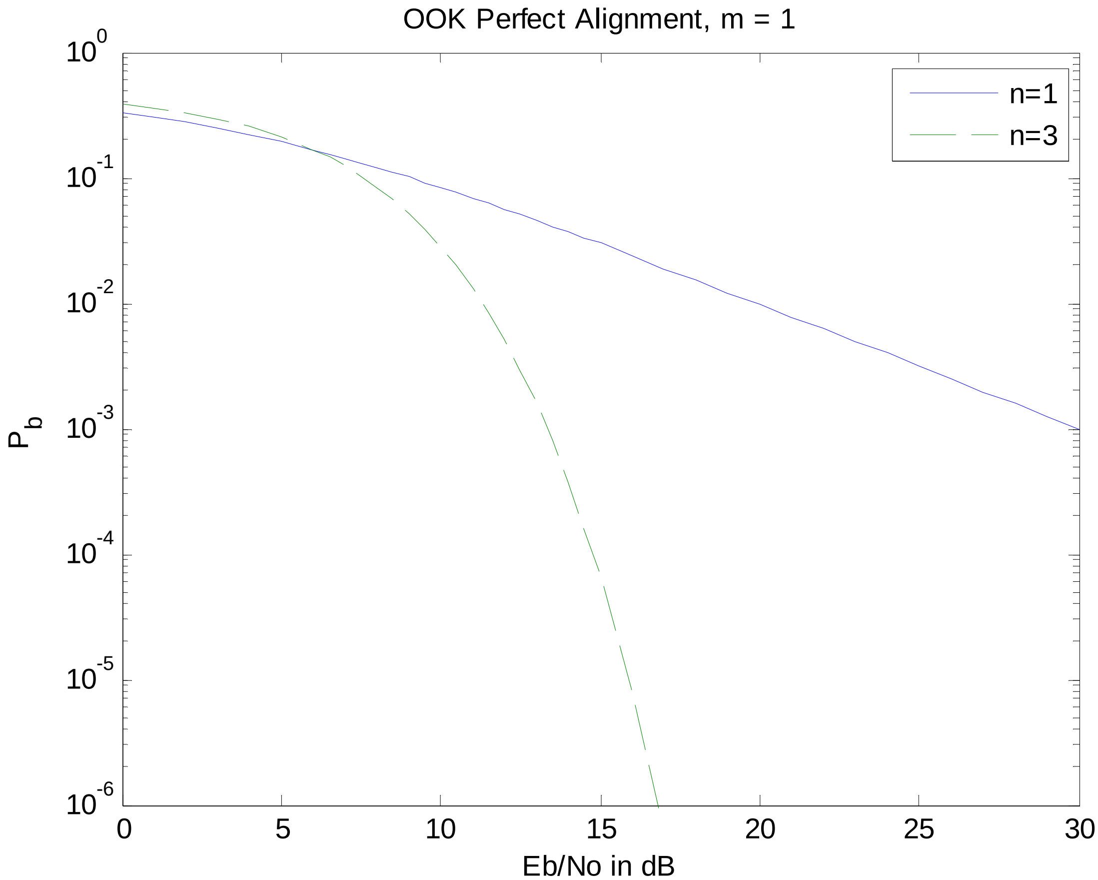

Figure 9. Bit Error Probability Performance for Non-Coherent OOK in a Fading Channel where m = 1 and n = 1, 3 respectively.

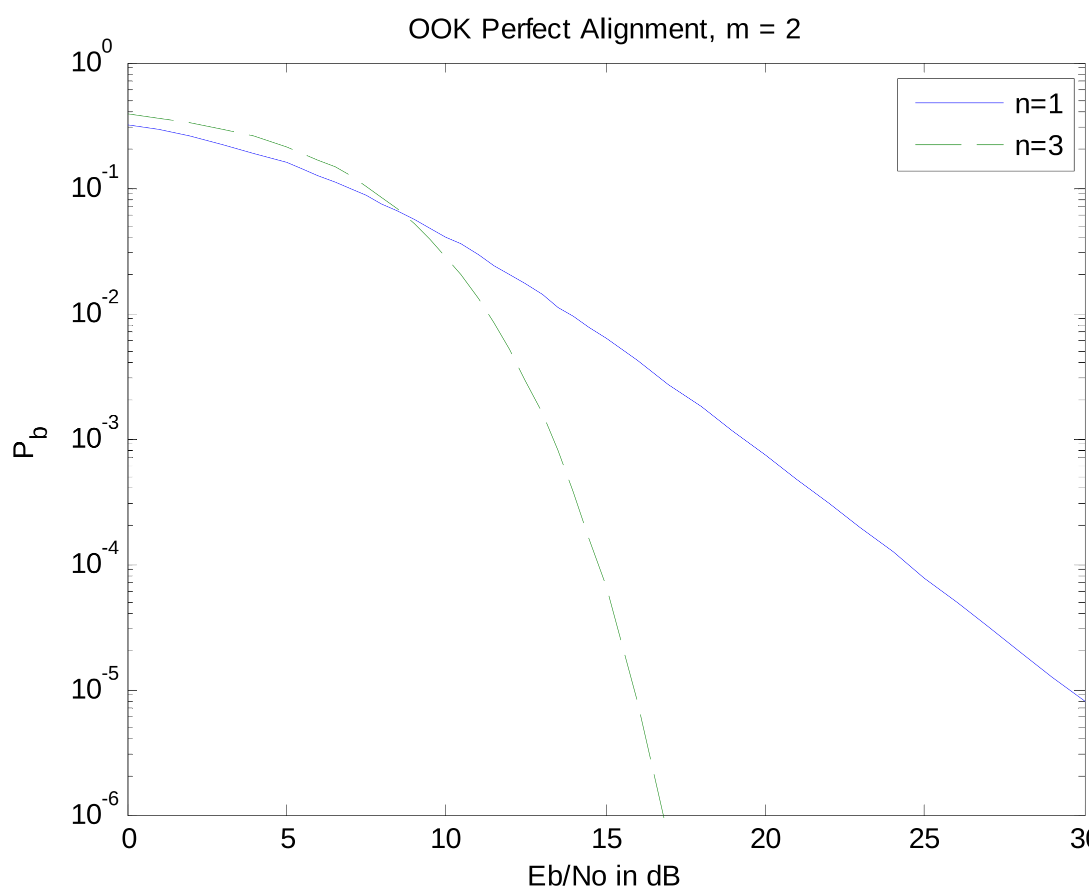

Figure 10. Bit Error Probability Performance for Non-Coherent OOK in a Fading Channel where m = 2 and n = 1, 3 respectively.

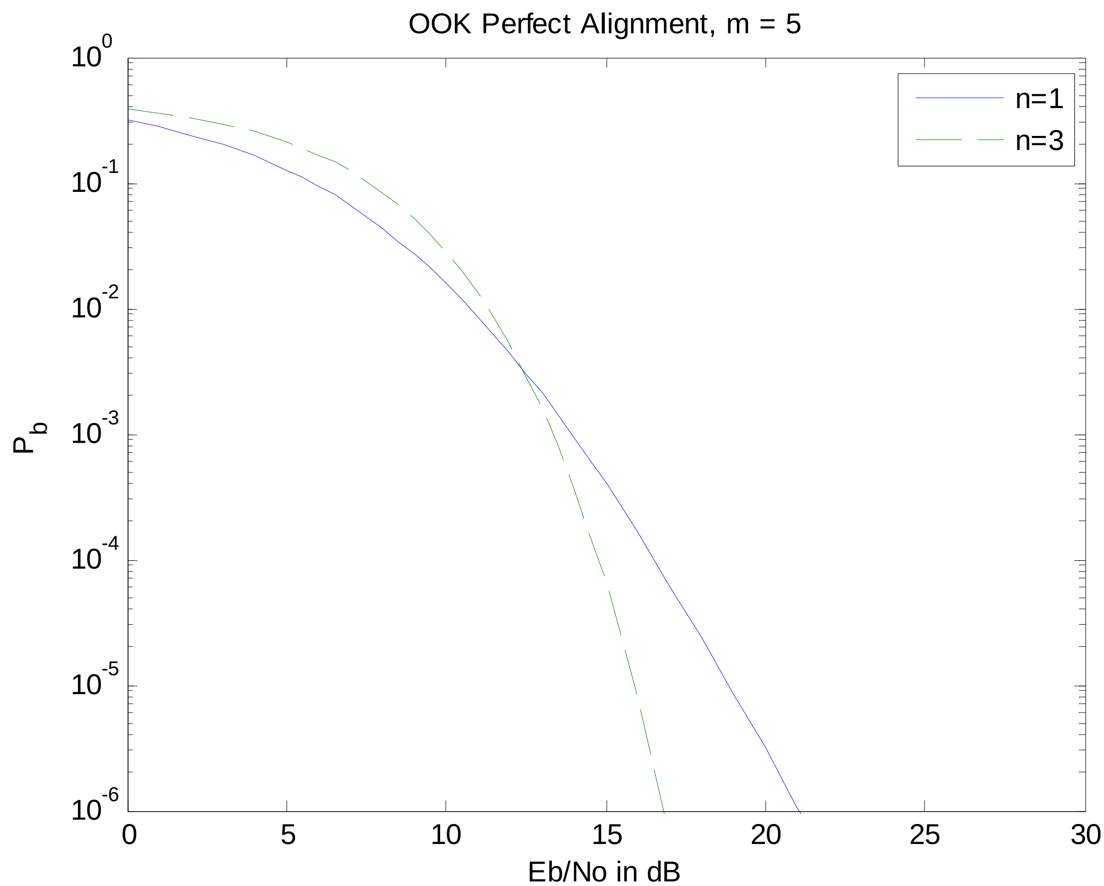

Figure 11. Bit Error Probability Performance for Non-Coherent OOK in a Fading Channel where m = 5 and n = 1, 3 respectively.

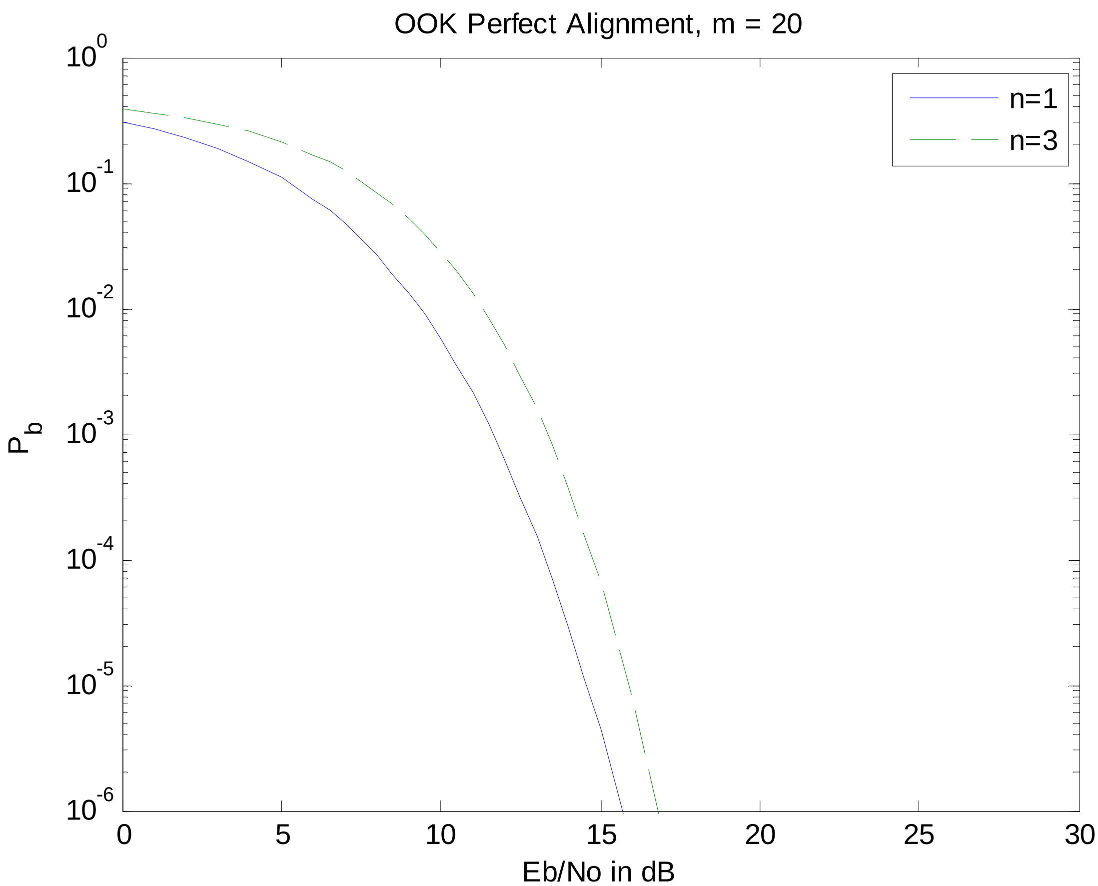

Figure 12. Bit Error Probability Performance for Non-Coherent OOK in a Fading Channel where m = 20 and n = 1, 3 respectively. The Non-coherent Combining Effect Shows a Coding Loss as *m* Grows Larger (Less Fading, the Channel Approaches the Gaussian Noise Channel).

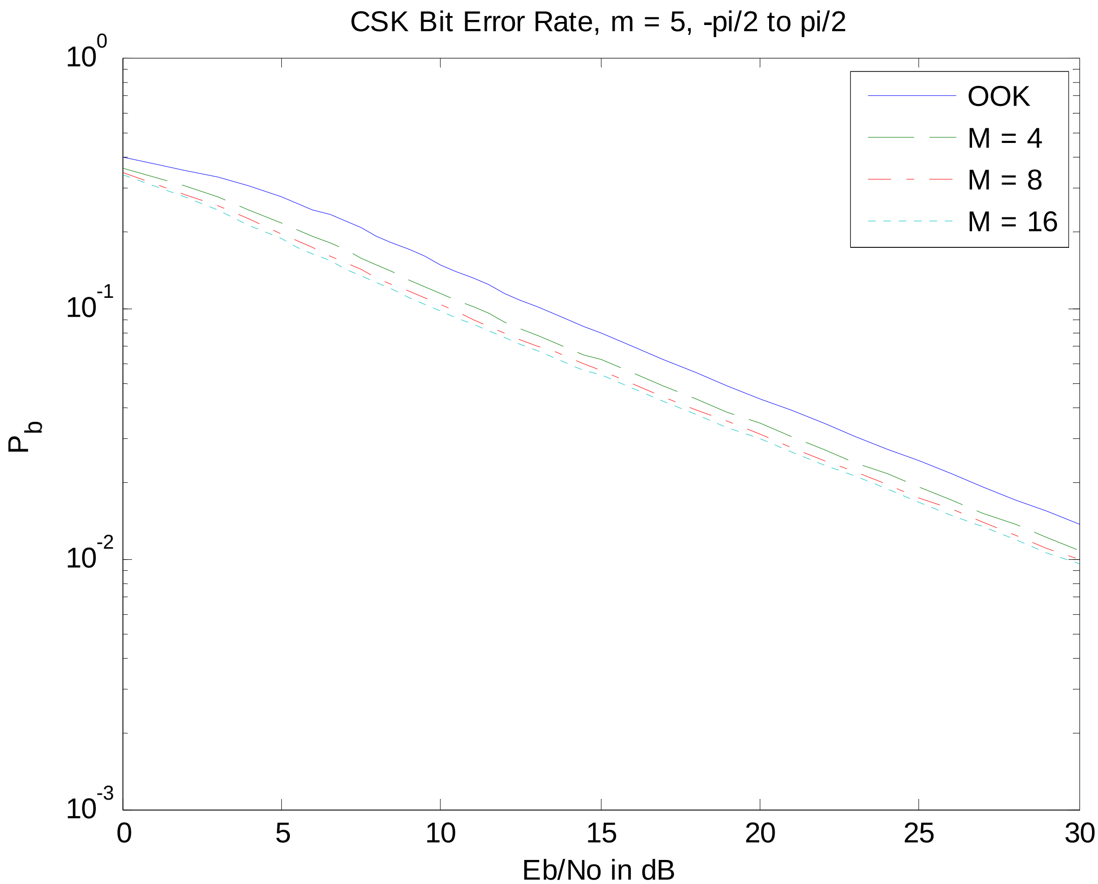

Figure 13. Bit Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 5, M = 2, 4, 8, 16, n = 1 and the Uniform Distribution Runs from $\frac{-\pi}{2}$ to $\frac{\pi}{2}$.

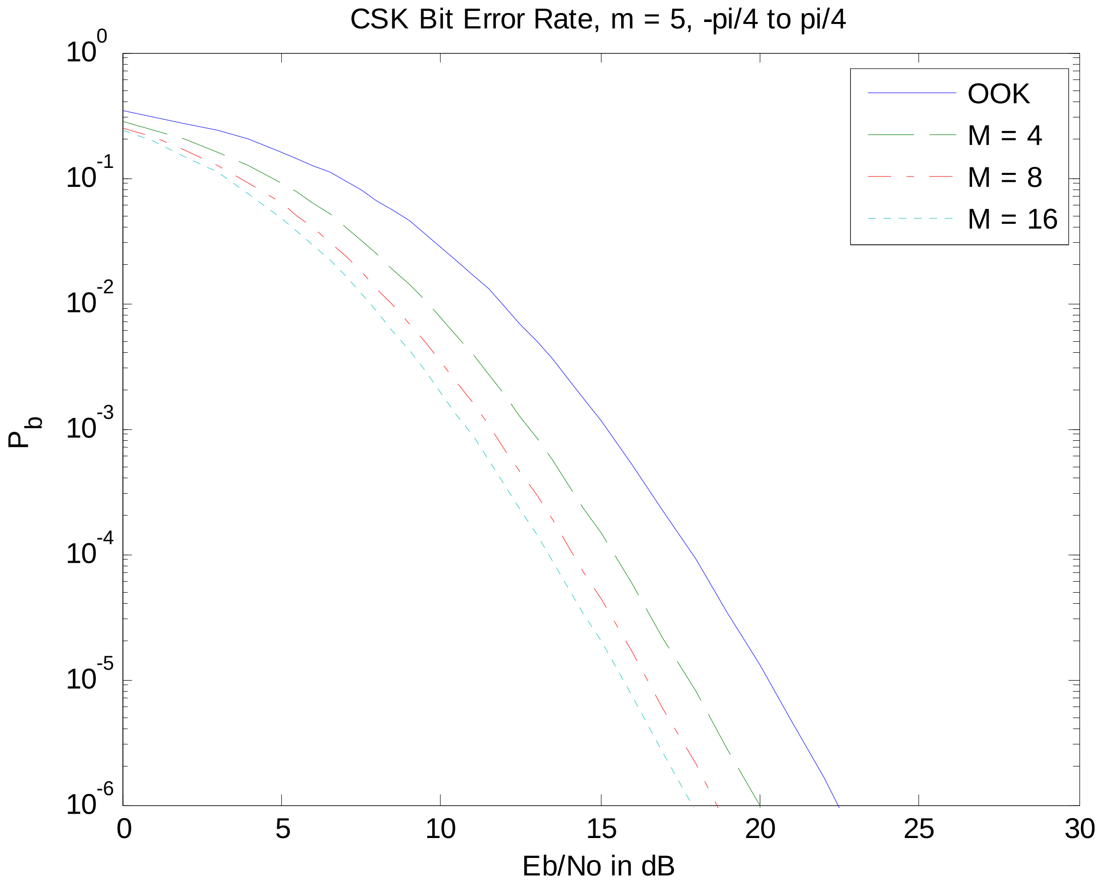

Figure 14. Bit Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 5, M = 2, 4, 8, 16, n = 1 and the Uniform Distribution Runs from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$.

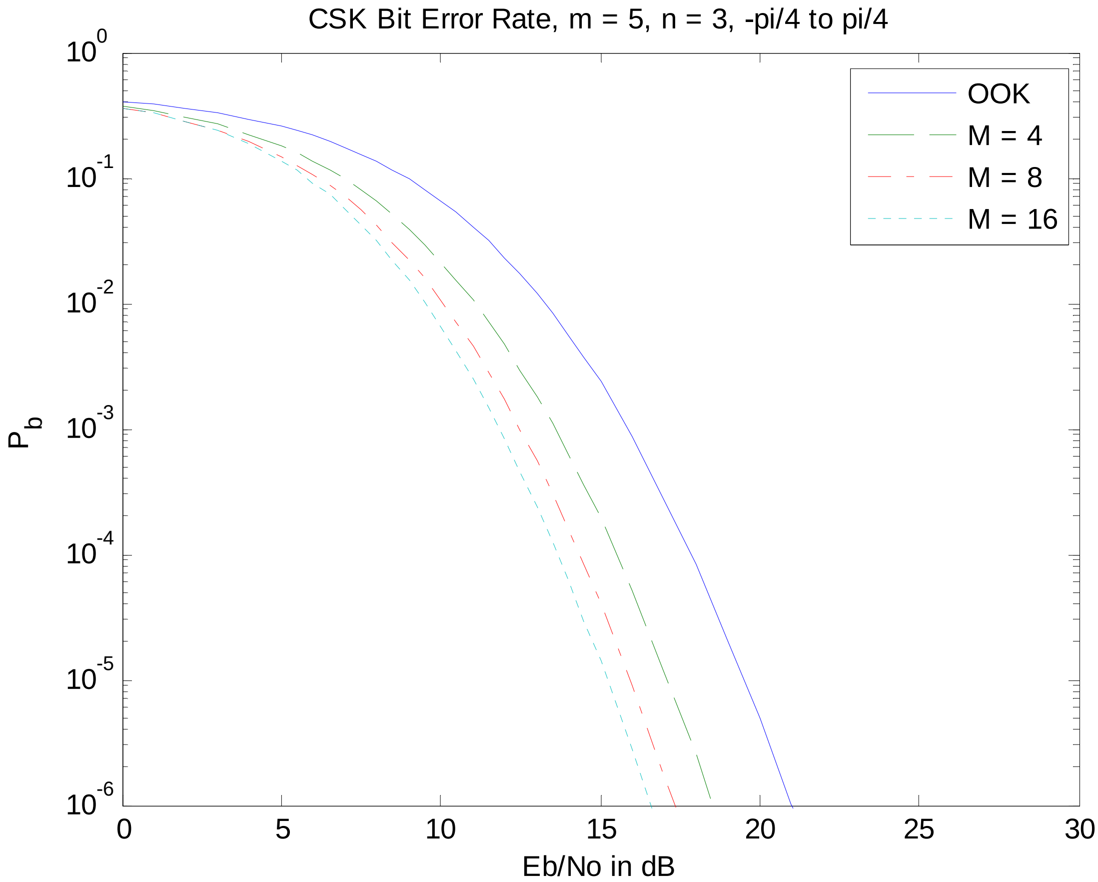

Figure 15. Bit Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 5, M = 2, 4, 8, 16, n = 3 and the Uniform Distribution Runs from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$.

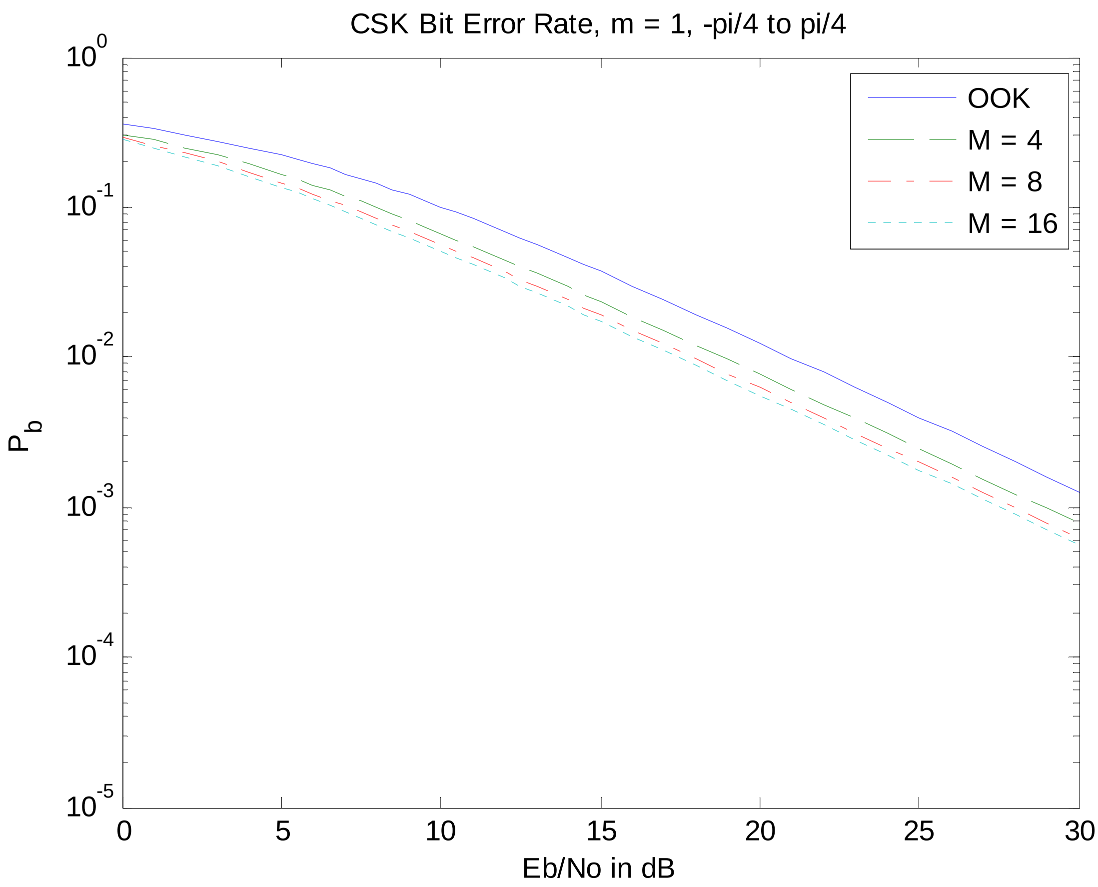

Figure 16. Bit Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 1, M = 2, 4, 8, 16, n = 1 and the Uniform Distribution Runs from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$.

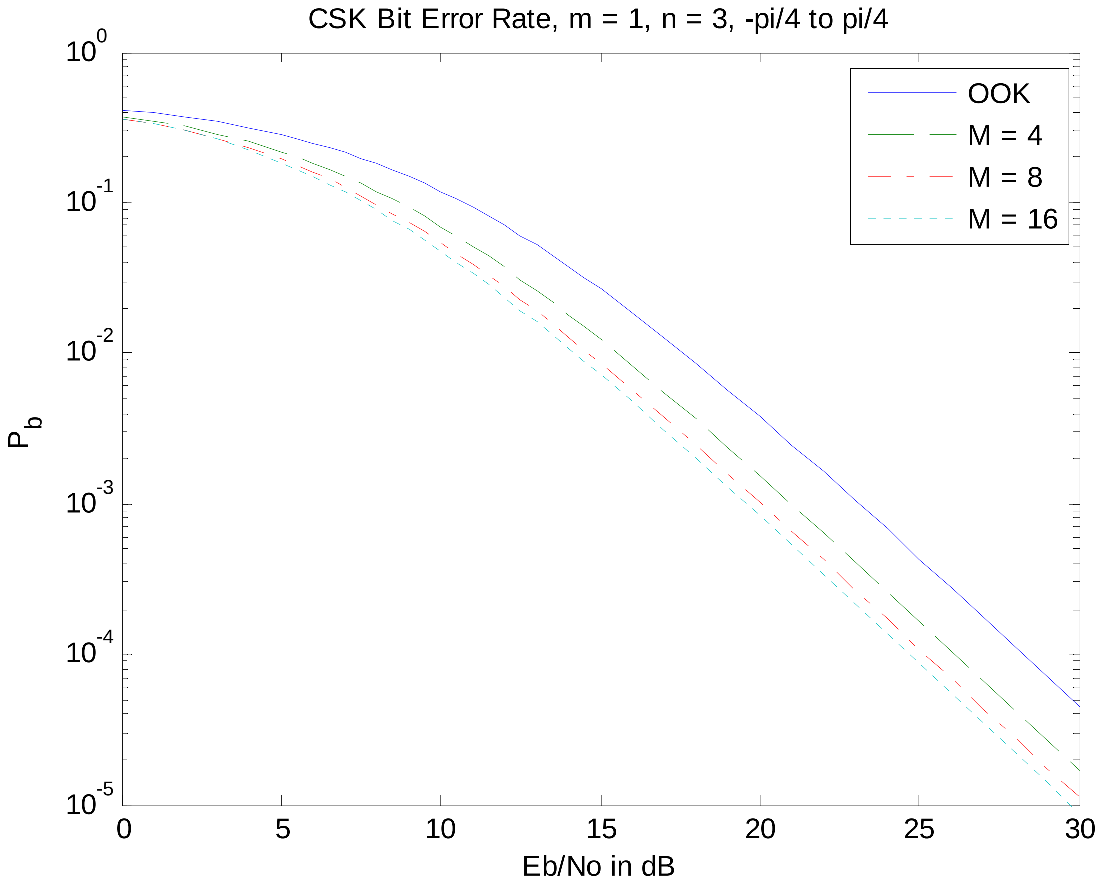

Figure 17. Bit Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 1, M = 2, 4, 8, 16, n = 3 and the Uniform Distribution Runs from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$.

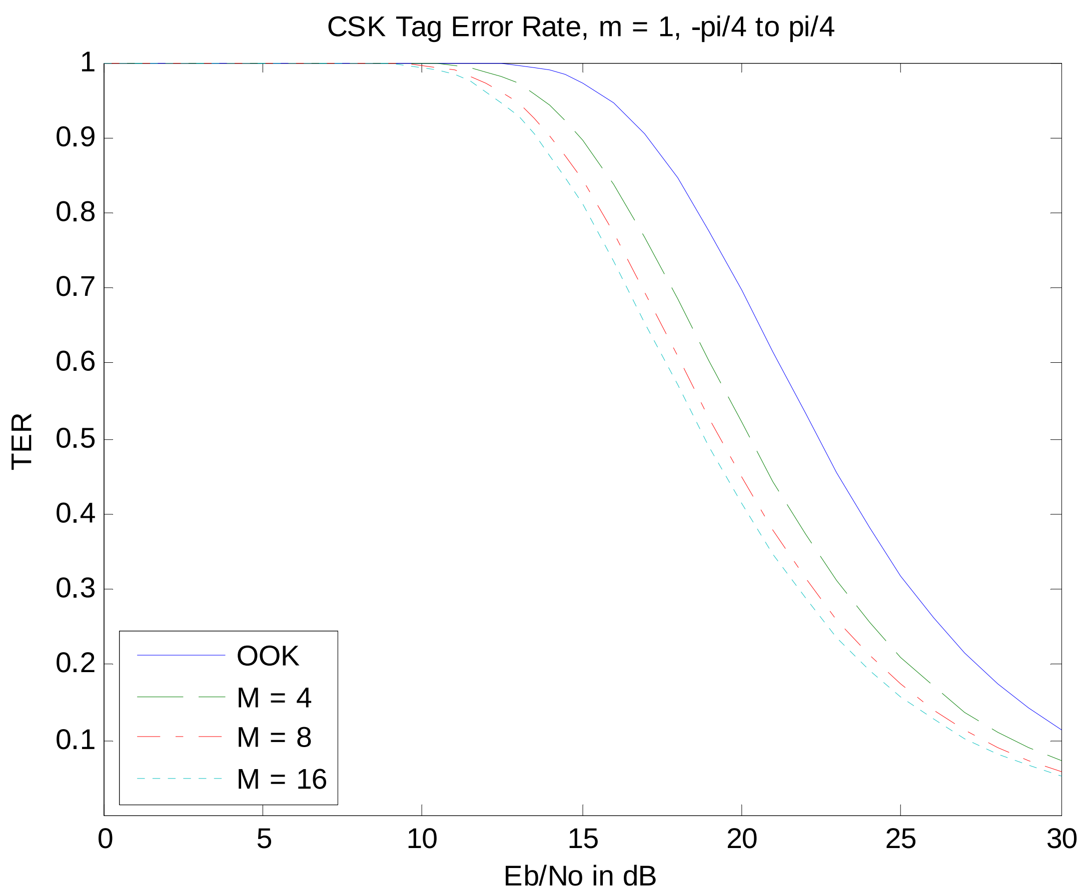

Figure 18. Tag Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 1, M = 2, 4, 8, 16, n = 1 and the Uniform Distribution Runs from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$.

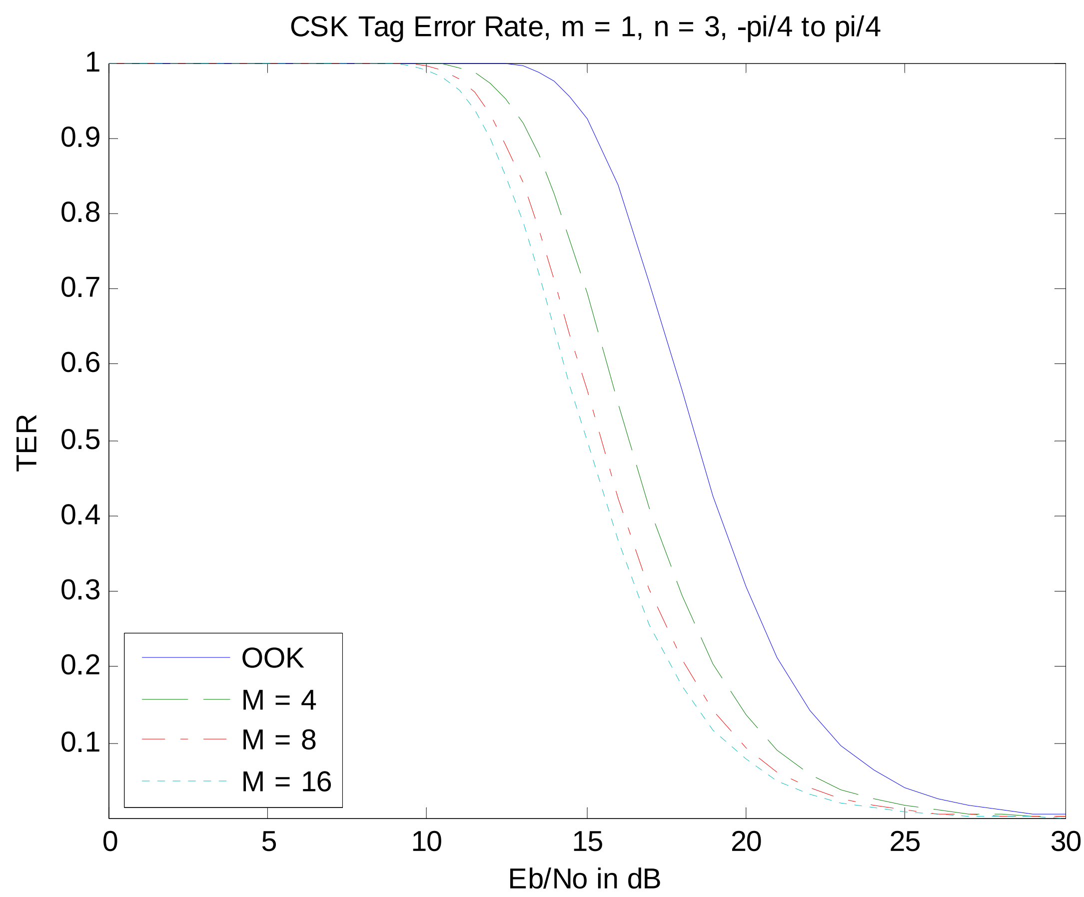

Figure 19. Tag Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 1, M = 2, 4, 8, 16, n = 3 and the Uniform Distribution Runs from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$.

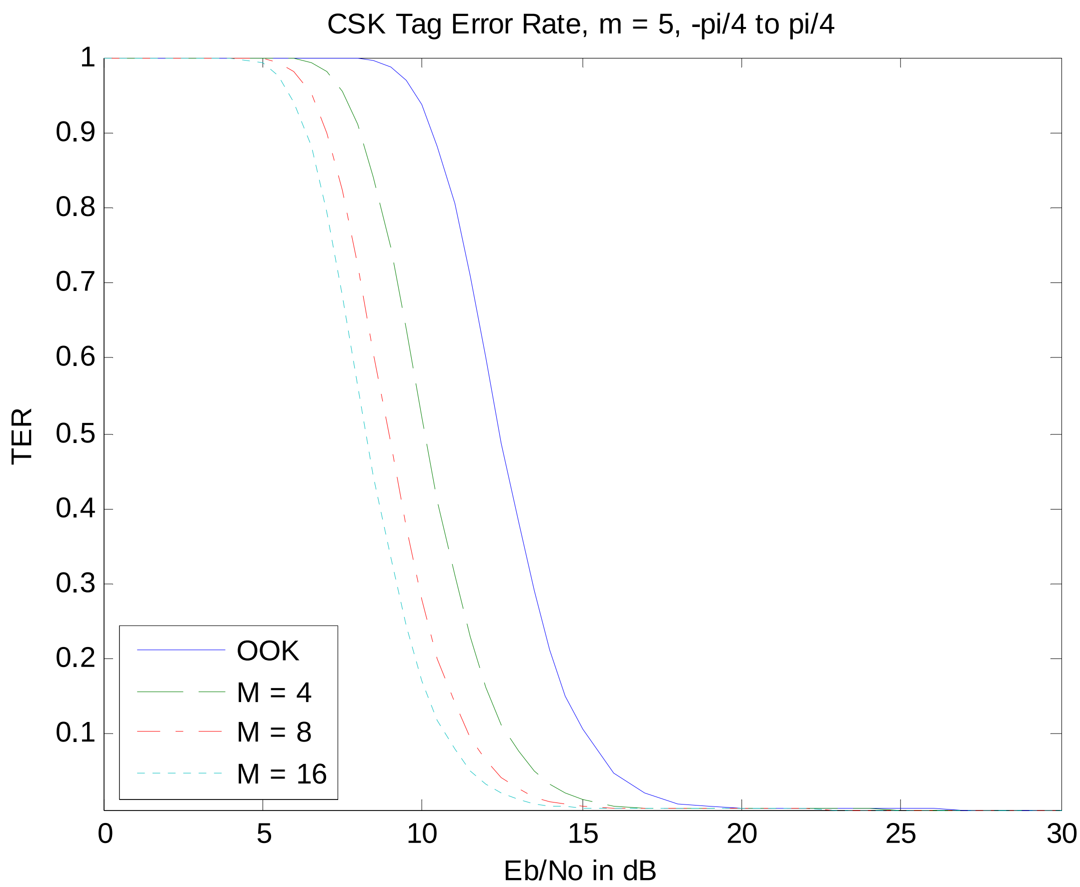

Figure 20. Tag Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 5, M = 2, 4, 8, 16, n = 1 and the Uniform Distribution Runs from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$.

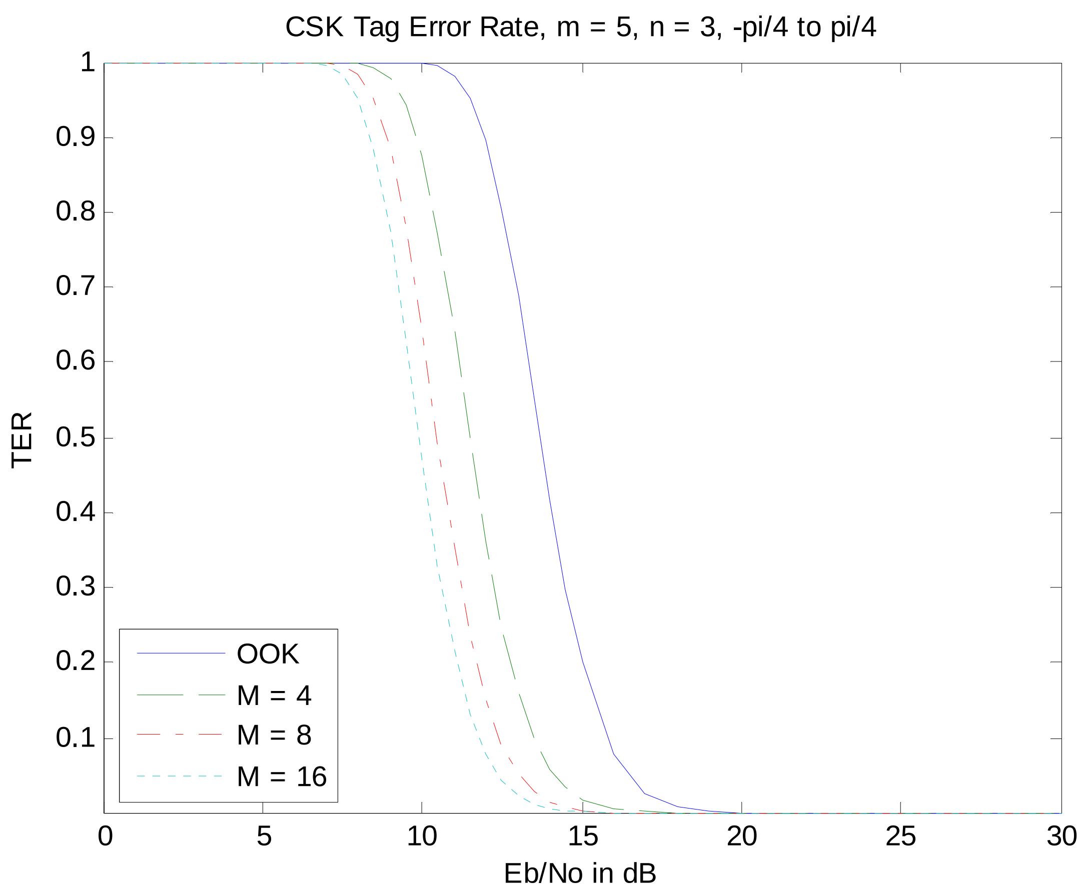

Figure 21. Tag Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 5, M = 2, 4, 8, 16, n = 3 and the Uniform Distribution Runs from $\frac{-\pi}{4}$ to $\frac{\pi}{4}$.

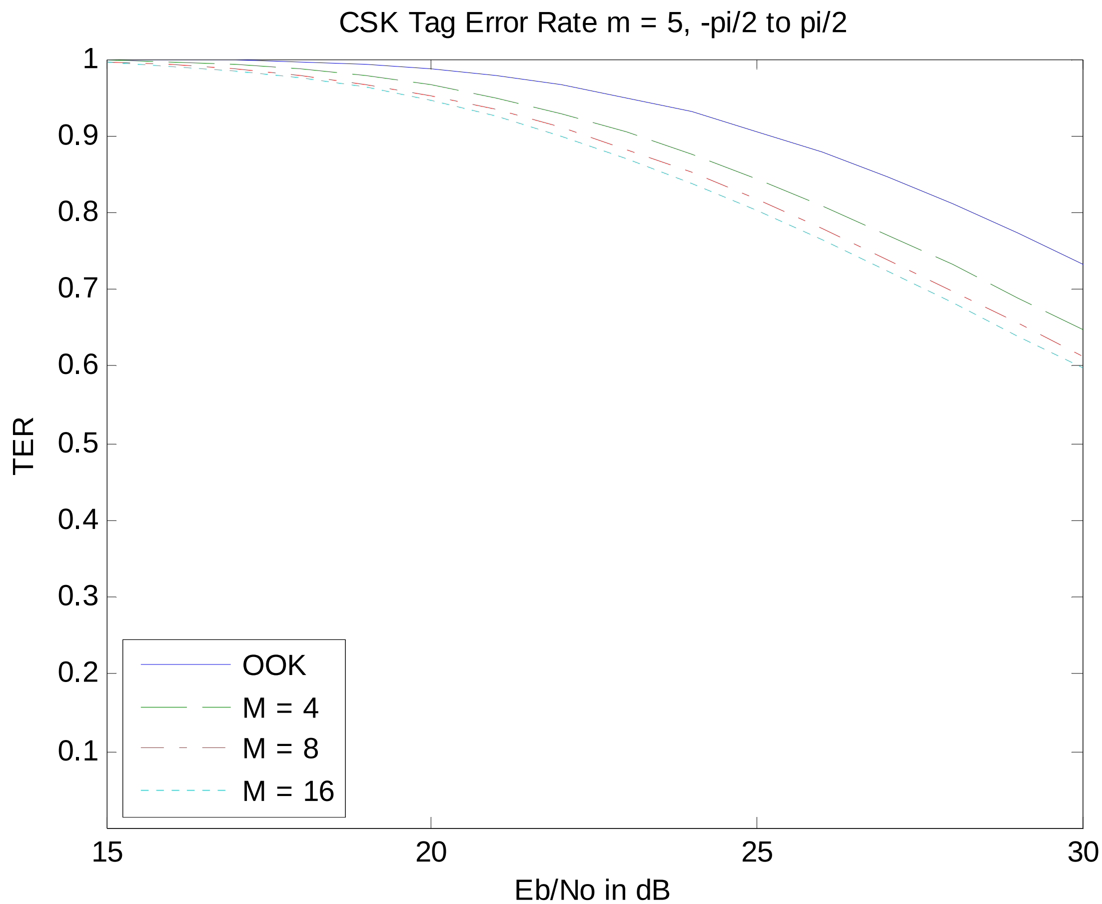

Figure 22. Tag Error Probability Performance for Non-Coherent M-CSK in a Fading Channel where m = 5, M = 2, 4, 8, 16, n = 1 and the Uniform Distribution Runs from $\frac{-\pi}{2}$ to $\frac{\pi}{2}$.

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VI. CONCLUSION

A. CONCLUSIONS

The results show that repetition coding both improves and reduces read performance depending on the fading environment. When the environment resembles the expected real world environment, repetition coding for the most part reduces read reliability due to non-coherent combining loss.

The best way to increase read reliability performance through coding is to use code shift keying with a high M value and/or more powerful codes such as the Hamming codes (Proakis, 2001). Results show a consistent 4 to 5 dB reduction in signal-to-noise ratio needed to achieve a certain error probability performance level when using 16-CSK compared to OOK.

The overall best way to increase read reliability performance comes from ensuring the best alignment of tag and reader to ensure that the highest possible amount of power can be received.

B. FUTURE WORK

There are many possibilities for future work to try to increase RFID read reliability performance. Experimenting with a Hamming code in place of the repetition code could yield further gains, since Hamming code works much better in a non-coherent system. Exploring the effects of multiple tags in a single reader interrogation zone, which can lead to tag data collision, could lead to improved deconfliction schemes. Finally, a real world test of various RFID systems to test the actual effects of the fading environment could be helpful to understanding the best modulation scheme to use to increase performance.

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APPENDIX. NAKAGAMI-M PDF

The Nakagami-m probability density function equation is used extensively in this study to model different fading environments. Equation (1) shows the density function used and the paragraph following the equation explains its parameters.

Figure 23 shows the output of the probability density function when different values of *m* are used in the equation.

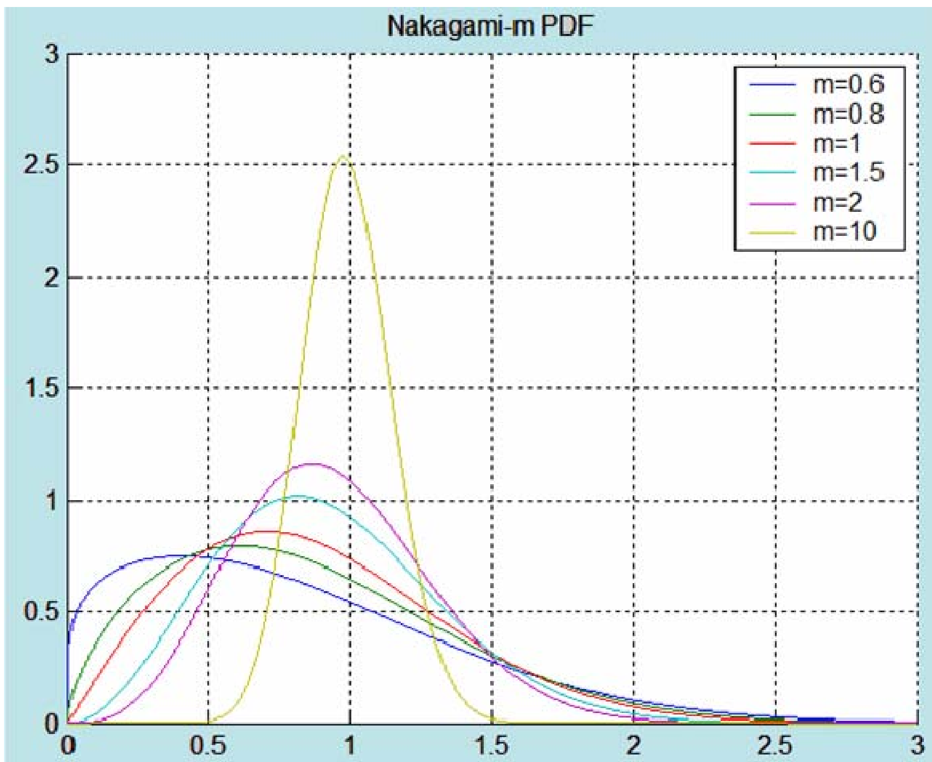

Figure 23. Nakagami-m Probability Density Function using Various *m* Values (from [10])

The important thing to note is that when a large line-of-sight component exists (large m), the probability of an average received signal power is high. In contrast, a smaller line-of-sight component leads to a high probability that the received signal power

will be below average due to the larger multipath components. The lower received signal power results in a lower signal-to-noise ratio and energy per bit ratio, thus reducing system performance. The Nakagami-m probability density function makes it easy to vary the line-of-sight component, which allows for repeated testing of various fading environments.

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